Inclinations and black hole masses of Seyfert 1 galaxies

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ABSTRACT

A tight correlation of black hole mass (M_{BH}) and central velocity dispersion (σ) has been found recently for both active and quiescent galaxies. By applying this correlation, we develop a simple method to derive the inclination angles for a sample of 11 Seyfert 1 galaxies that have both measured central velocity dispersions and black hole masses estimated by reverberation mapping. These angles, with a mean value of 36^o that agrees well with the result obtained by fitting the iron Kα lines of Seyfert 1s observed with *ASCA*, provide further support to the orientation-dependent unification scheme of AGN. A positive correlation of the inclinations with observed FWHMs of Hβ line and a possible anti-correlation with the nuclear radio-loudness have been found. We conclude that more accurate knowledge on inclinations and broad line region dynamics is needed to improve the black hole mass determination of AGN with the reverberation mapping technique.

Subject headings: black hole physics – galaxies: active – galaxies: nuclei – galaxies: Seyfert.

1. Introduction

Supermassive black hole is believed to be an essential part of active galaxy and quasar (Lynden-Bell 1969; Rees 1984). Recently a lot of evidence has also been found for the existence of supermassive black holes in nearby quiescent galaxies (Kormendy & Richstone 1995; Magorrian et al. 1998). A significantly tight correlation of black hole mass (M_{BH}) with the bulge velocity dispersion (σ) was found for nearby galaxies (Gebhardt et al. 2000a; Ferrarese & Merritt 2000). More recent studies indicated that some Seyfert galaxies with M_{BH} measured by reverberation mapping method follow the same M_{BH}-σ relation as for

normal galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001), which implies that this relation may be universal for galaxies. This relation strongly suggests a tight connection between the formation and evolution of the supermassive black hole and the galactic bulge, though the nature of this connection is still unclear.

The black hole masses of some active galactic nuclei (AGN) have been recently estimated by the reverberation mapping technique (Wandel, Peterson & Malkan 1999; Ho 1999; Kaspi et al. 2000). With this technique, the broad line region (BLR) size can be measured using the lag between the variability of continuum and emission line fluxes. The black hole mass can be then estimated from the BLR size and the characteristic velocity (determined by the full width at half-maximum (FWHM) of emission line). However, it may not be so straitforward to estimate the characteristic velocity of BLR according to the observed FWHMs of emission lines (Fromerth & Melia 2000). Many effects, especially the inclination and BLR geometry, can lead to larger uncertainties to the estimation of black hole mass using reverberation mapping (Krolik 2001).

Inclination is an important ingredient in the orientation dependent unified scheme of AGN (Urry & Padovani 1995), but it is not easy to be derived directly from observations. By fitting the observed iron Kα line profile with the accretion disk model, Nandra et al. (1997) estimated the inclinations, with a mean value of 30^o, for 18 Seyfert 1 galaxies. Although with large uncertainties, their result suggested that the inclinations of Seyfert 1s are small, consistent with Seyfert 1/2 unification scheme (Antonucci & Miller 1985). Moreover, numerous observations have shown the evidence for the lack of edge-on Seyfert 1 galaxies (Keel 1980) and suggested that Seyfert 1 galaxies have the dusty torus with half opening angles of 40^o to 60^o (Osterbrock & Martel 1993; Ho, Fillippenko & Sargent 1997; Schmitt et al. 2001). Therefore, the inclinations of Seyfert 1 galaxies are generally expected to be small, though further evidence is obviously needed.

If the M_{BH}-σ relation is valid for Seyfert galaxies, this provides an independent way to determine M_{BH} from the reverberation mapping. Using M_{BH} derived from the measured stellar velocity dispersion and assuming a simple BLR geometry, we develop a method to derive the inclinations for 11 Seyfert 1 galaxies with both measured central velocity dispersions and estimated black hole masses by reverberation mapping. Our results are supported by several correlation studies and are consistent with previous knowledge of inclination effects of AGN.

2. Black hole mass determinations of AGN

According to the reverberation mapping technique, the black hole mass can be estimated by a virial form,

$$\mathrm{M}_{\mathrm{rev}} = \frac{V^2 R}{G}, \tag{1}$$

provided that the BLR region of AGN is gravitational bounded and has a Keplerian characteristic velocity (V). The BLR size (R) can be derived by the lag between the variability of continuum and broad emission line. Assuming AGN having random inclinations, Wandel et al. (1999) and Kaspi et al. (2000) related the BLR characteristic velocity to the FWHM of Hβ emission line by $V = (\sqrt{3}/2)V_{\mathrm{FWHM}}$. However, as pointed recently by McLure & Dunlop (2001), the assumption of random inclinations seems unrealistic for quasars. Many observational studies also indicated that Seyfert 1 galaxies are probably not viewed at all inclinations (Osterbrock & Martel 1993; Ho et al. 1997; Nandra et al. 1997; Schmitt et al. 2001).

On the other hand, the BLR dynamics of AGN has not been well understood yet. The simplest case may be described as circular orbits confined to the disk plane, but the real case is probably much more complicated. The same as that assumed for quasars, the BLR velocity of Seyfert 1s may be better represented by a combination of a random isotropic component, with characteristic velocity V_r, and a component in the disk plane, with characteristic velocity V_p (Wills & Browne 1986). Therefore, the observed FWHM of emission line will be given by

$$V_{\mathrm{FWHM}} = 2(V_r^2 + V_p^2 \sin^2 i)^{1/2}, \tag{2}$$

where i is the inclination angle of the disk normal relative to the line of sight. Assuming that V_p is significantly larger than V_r and that i lies randomly between 0 and 46^o, McLure & Dunlop (2001) has reproduced the distribution of observed Hβ FWHMs for a sample of AGN using the above formula. If we relate the observed emission line FWHM and BLR characteristic velocity with eq. (2), the black hole mass of AGN can be obtained by

$$\mathrm{M}_{\mathrm{BH}} = \frac{1}{4(\sin^2 i + \mathrm{A}^2)} \frac{V_{\mathrm{FWHM}}^2 R}{G}, \tag{3}$$

where $A = V_r/V_p$. In most recent studies, the black hole mass ($\mathrm{M}_{\mathrm{rev}}$) determined by reverberation mapping is based on the assumption of random inclinations and is expressed as $\mathrm{M}_{\mathrm{rev}} = \frac{3}{4}\frac{V_{\mathrm{FWHM}}^2 R}{G}$ (Wandel et al. 1999; Kaspi et al. 2000). If the inclination effect is considered, using eq. (3) we can derive the inclination angle by:

$$i = \arcsin\left(\sqrt{\frac{\mathrm{M}_{\mathrm{rev}}}{3\mathrm{M}_{\mathrm{BH}}} - \mathrm{A}^2}\right). \tag{4}$$

If M_{BH} of AGN can be derived independently by other methods, we can use eq. (4) to estimate the inclinations of AGN. Fortunately a tight relation between black hole mass and central velocity dispersion seems to exist for AGN, therefore M_{BH} can be directly derived from the measured central velocity dispersion. According to Gebhardt et al. (2000a), the M_{BH}-σ relation is:

$$M_{BH} = 1.2 \times 10^8 M_\odot (\sigma/200 \text{ km s}^{-1})^{3.75}. \tag{5}$$

Using a slightly steeper slope found by Ferrarese & Merritt (2000) has no significant effect on our results.

3. Inclination angles of Seyfert 1 galxies

We collected 11 Seyfert 1 galaxies with both measured central velocity dispersion (σ) and estimated black hole masses (M_{rev}) by reverberation mapping (Wandel et al. 1999; Ho 1999; Kaspi et al. 2000). Their σ and M_{rev} values, together with the observed FWHMs of Hβ line (Wandel et al. 1999; Ho 1999) and the nuclear radio-loudness (Ho & Peng 2001), are summarized in Table 1. Seven sources have σ values from high quality measurements of Ferrarese et al. (2001) and Di Nella et al. (1995). The σ values of other four sources were adopted from Nelson & Whittle (1995). The uncertainties of M_{rev} and V_{FWHM} for NGC 3516 and NGC 4593 are unavailable in literature and were assumed to be 30% and 5%, respectively.

The inclinations of these 11 Seyfert 1s can be estimated using eq. (4) and eq. (5). For simplicity we further assume $A \ll M_{rev}/3M_{BH}$ in eq. (4), which is equivalent to the approximation that the BLR characteristic velocity is dominated by the component in the disk plane (McLure & Dunlop 2001). Under this assumption, we derived the inclinations for 11 Seyfert 1s (see Table 1 and Figure 1). The errors of i were estimated from the uncertainties of both σ and M_{rev}. The inclination angles we derived are in a range from 20^o to 60^o, with a mean value of 36.2^o. This agrees with the result obtained by fitting the observed iron Kα line in X-ray band with accretion disk model (Nandra et al. 1997), and is consistent with the expectation of unified scheme of AGN (Antonucci & Miller 1985). In Figure 2, we can clearly observe an apparent positive correlation between inclinations and observed Hβ FWHMs. A minimum χ^2 fit considering the errors of both parameters gives, $\sin(i) = (0.23 \pm 0.09) + (0.086 \pm 0.024)(V_{FWHM}/1000\text{km s}^{-1})$, with χ^2 and probability of 7.13 and 62%, respectively. The zero slope is less favored because it produces a larger χ^2 (22.78) with a probability of 1% only. A simple Spearman test gives the correlation coefficient $R = 0.78$, with have a probability of $P = 4.47\times10^{-3}$ to occur by chance. We have also applied the bootstrap method to investigate the uncertainty of correlation coefficient by considering

the uncertainties of both parameters, and obtained $\langle R \rangle = 0.58 \pm 0.18$, which indicates a moderately significant correlation. In Figure 3, we plotted the inclinations against the nuclear radio loudness, defined by the ratio between 5 GHz nuclear radio luminosity and B-band nuclear optical luminosity (Ho & Peng 2001). Because there are serious contaminations to the luminosity of Seyfert nucleus from the host galaxy, using the nuclear radio-loudness can maximumly diminish such contaminations and better describe the nature of Seyfert nuclei. Although only seven sources with available data for nuclear radio-loudness, Figure 3 still displays the trend that Seyfert 1s with larger nuclear radio-loudness may have smaller inclinations. These results seem to be consistent with our knowledge on the inclination effects of quasars and AGN (Wills & Browne 1986; Wills & Brotherton 1995).

If the characteristic velocity of BLR is dominated by the component in the disk plane, the *intrinsic* FWHM of Hβ emission line can be approximated by the observed FWHM divided by $\sin(i)$. In Figure 4 we show the distributions of intrinsic FWHMs of Hβ line and M_{BH}. Two narrow line Seyfert 1s (NLS1s), NGC 4051 and Mrk 110, locate in the lower-left corner of Figure 4, though their inclination angles, estimated to be 19.6^o and 37.4^o, are not significantly smaller than those of other broad line Seyfert 1s. This indicates that the narrowness of emission lines of NLS1 may not be simply due to the inclination effects, but is probably more related to their smaller black hole masses. These NLS1s may have accretion rates close to Eddington limit (Boller, Brandt & Fink 1996). For most broad line Seyfert 1s, the Eddington ratios (L/L_{Edd}) are in the range of 0.1 to 0.01 (Wandel et al. 1999), which are significantly lower than those of NLS1s.

4. Discussion

Assuming a Kelperian rotation of BLR and Seyfert 1s following the same M_{BH}-σ relation as normal galaxies, we develop a method to derive the inclinations of 11 well studied Seyfert 1 galaxies. The values of these inclinations derived by us seem to be supported by a positive correlation with the observed Hβ FWHMs and a possible anti-correlation with the nuclear radio loudness. Our results agree well with previous knowledge on inclinations of Seyfert 1s and are consistent with the expectation of unification scheme of AGN.

It is worth noting that the BLR dynamics may not be as simple as we assumed, though the Keplerian rotation of BLR have been confirmed by some recent studies (Peterson & Wandel 1999, 2000). The inclinations we derived for 11 Seyfert 1s may be regarded as upper limits because we assumed the characteristic velocity in the disk plane is the dominant component in BLR. Considering of the isotropic component will reduce the values of inclinations (see eq. (4)). VLBI study on the radio-loud Seyfert 1 galaxy 3C 120 derived a lower

inclination angle (about 10^o) based on the synchrotron self-Compton jet model (Ghisellini et al. 1993), which is smaller than but still marginally consistent with the value obtained by us.

We noticed that ratio between the black hole mass determined by reverberation mapping (M_{rev}) and the 'true' black hole mass (M_{BH}), can be approximated by $3\sin^2(i)$ (see eq. (4)). With the mean value of i (36.2^o) derived by us, we obtained $M_{rev}/M_{BH} = 1.05$ for Seyfert 1s. It means that the black hole mass estimated by the standard method of reverberation mapping, can still represent the 'true' black hole mass well if the inclination of Seyfert galaxy is not substantially different from 36.2^o. This may be the reason why Seyfert galaxies also follow the M_{BH}-σ relation even if the values of M_{BH} measured by reverberation mapping were adopted (Gebhardt et al. 2000b; Ferrarese et al. 2001). However, the M_{rev}/M_{BH} value changes from 0.35 to 2.25 if the inclination increases from 20^o to 60^o. Therefore, more accurate information about inclinations and the BLR dynamics of AGN will be undoubtedly helpful to the improvement of central black hole mass estimations with the reverberation mapping technique.

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Table 1: Data of Seyfert 1 galaxies

Name	σ (km/s)	Ref*	M_{rev} ($10^7 M_\odot$)	$V_{FWHM}(rms)$ (km/s)	log R_{nuc}	Inclination (^{o})
3C 120	162±20	1	$2.3^{+1.5}_{-1.1}$	2210±120	—	$22.0^{+9.3}_{-7.7}$
Mrk 79	130±9	2	$5.2^{+2.0}_{-2.8}$	6280±850	—	$58.5^{+21.7}_{-27.9}$
Mrk 110	86±5	2	$0.56^{+0.20}_{-0.21}$	1670±120	—	$37.4^{+9.2}_{-9.5}$
MrK 590	169±28	1	$1.78^{+0.44}_{-0.33}$	2170±120	1.62	$17.8^{+6.1}_{-5.9}$
Mrk 817	142±6	2	$4.4^{+1.3}_{-1.1}$	4010±180	1.21	$41.6^{+8.5}_{-7.5}$
NGC 3227	144±22	1	$3.9^{+2.1}_{-3.9}$	5530±490	1.12	$37.5^{+17.3}_{-25.4}$
NGC 3516	124±5	3	$2.3^{+0.69}_{-0.69}$	4760±240	0.78	38.3±7.6
NGC 4051	80±4	2	$0.13^{+0.13}_{-0.08}$	1230±60	0.87	$19.6^{+10.4}_{-6.6}$
NGC 4151	93±5	2	$1.53^{+1.06}_{-0.89}$	5230±920	0.49	$60.0^{+30.0}_{-30.6}$
NGC 4593	124±29	1	$0.81^{+0.24}_{-0.24}$	3720±180	—	21.6±10.5
NGC 5548	183±10	2	$12.3^{+2.3}_{-1.8}$	5500±400	1.24	$43.7^{+7.6}_{-6.9}$

*References: 1, Nelson & Whittle (1995); 2, Ferrarese et al. (2001); 3, Di Nella et al. (1995).

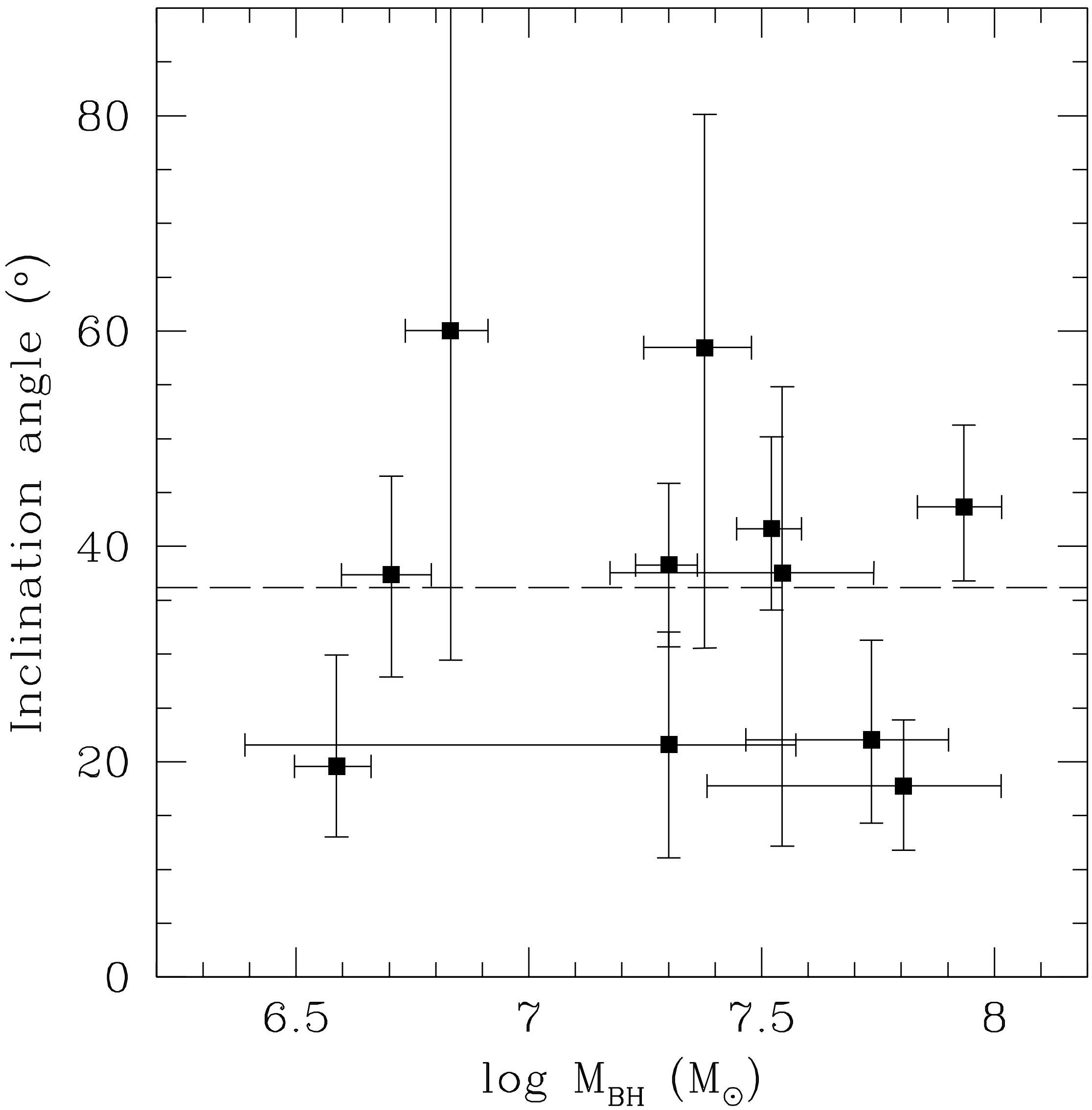

Fig. 1.— The derived inclination angles of 11 Seyfert 1 galaxies against the black hole masses determined by the M_{BH}-σ relation. The dashed line represents the mean value $\langle i \rangle = 36.2^o$.

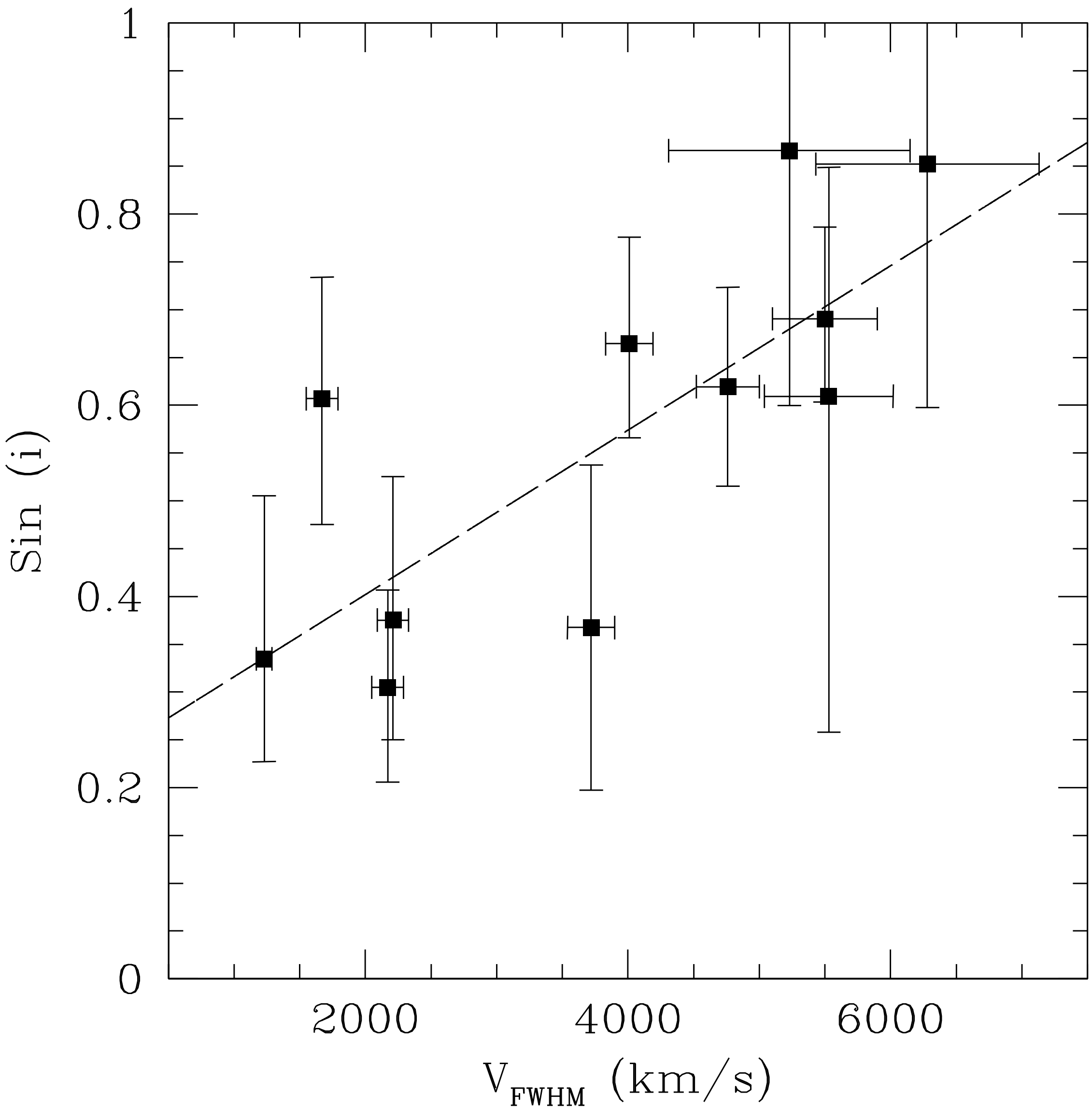

Fig. 2.— The inclination angles against the observed FWHMs of Hβ line. The dashed line shows the minimum χ^2 fit with errors of both parameters considered.

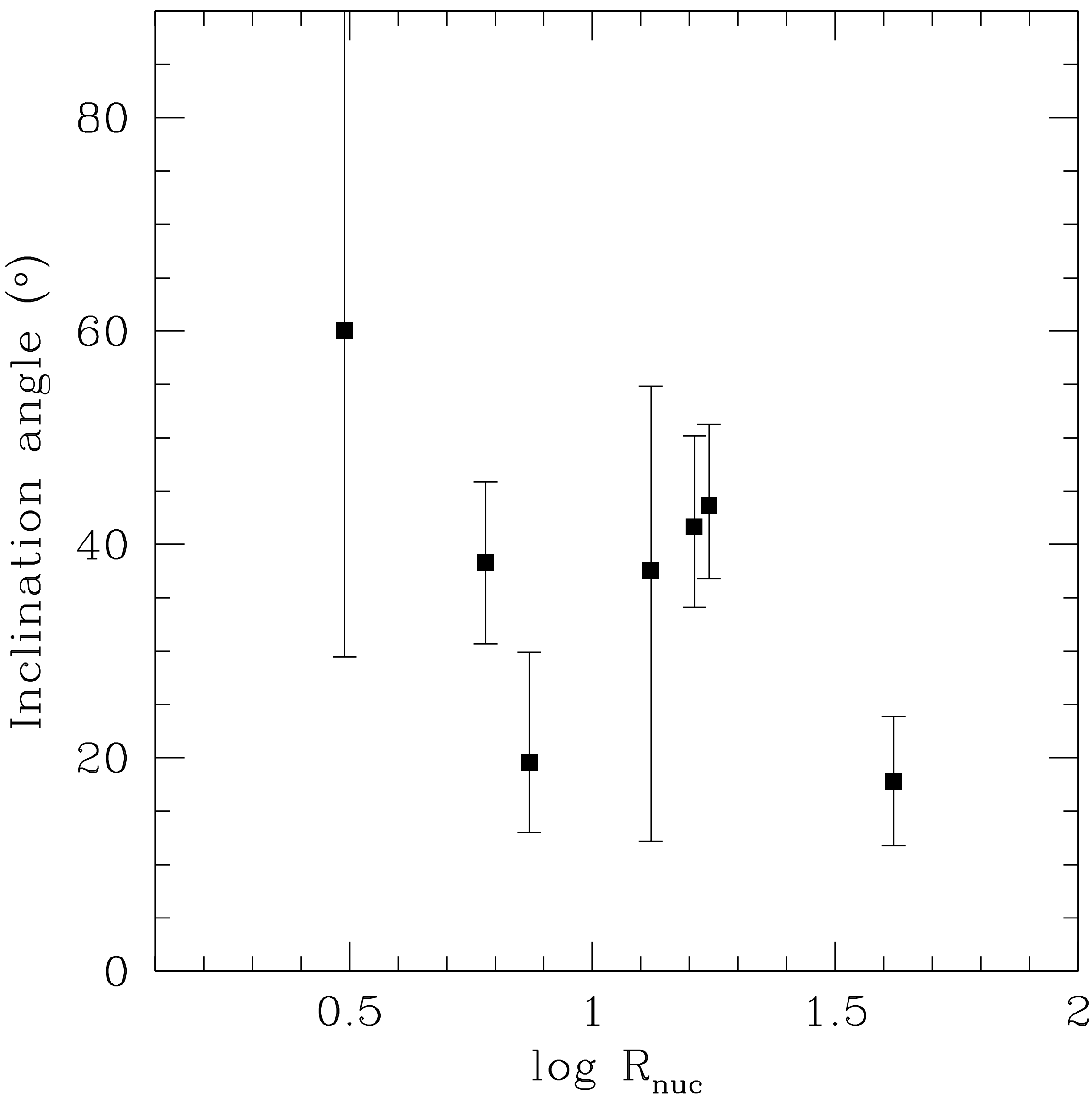

Fig. 3.— The inclination angles against the nuclear radio-loudness.

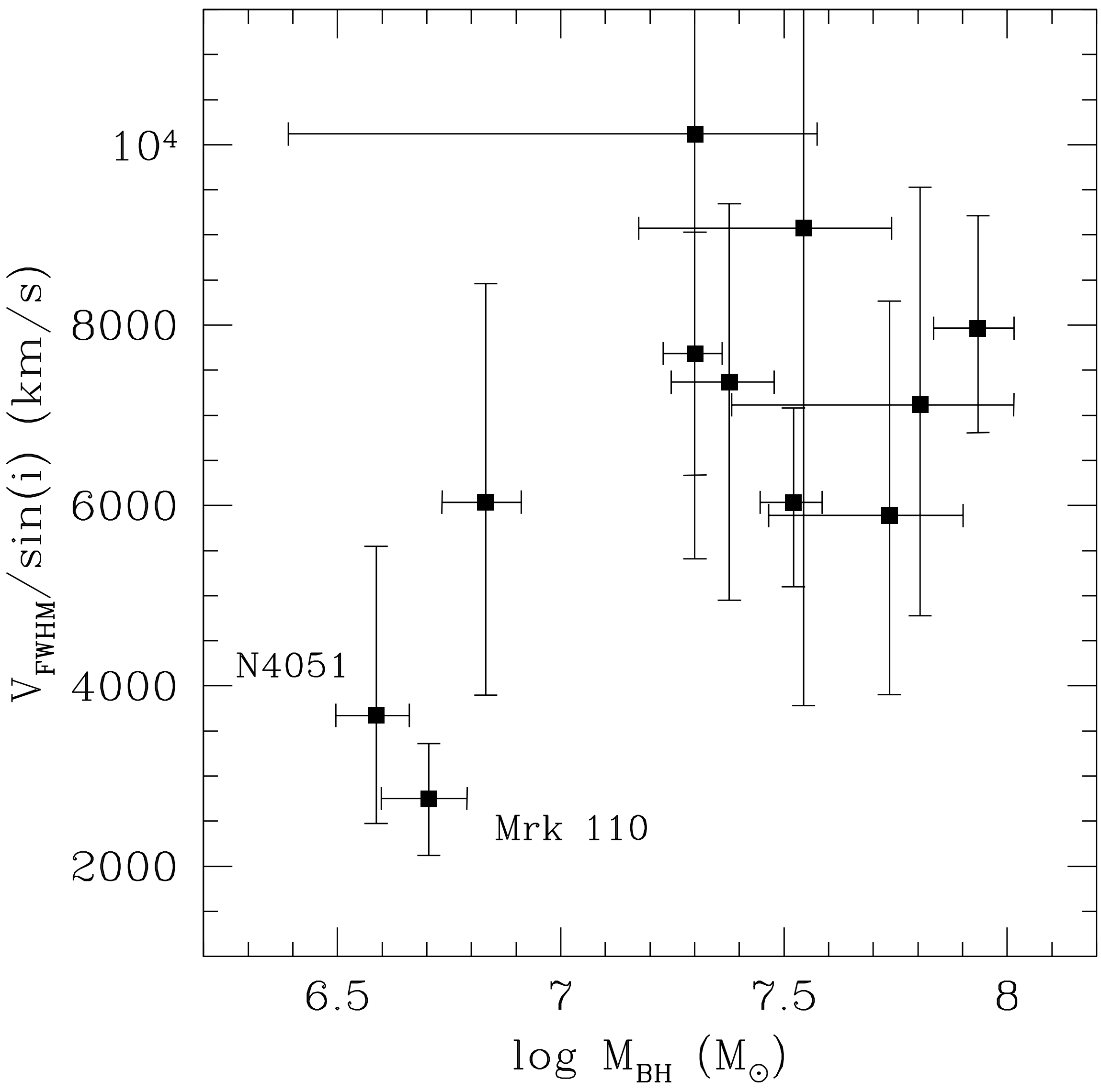

Fig. 4.— The intrinsic FWHMs of Hβ line against black hole masses determined by the M_{BH}-σ relation.